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Determination of the optimal configuration of energy recovery ventilator through virtual prototyping and DoE techniques

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Abstract

This study presents an approach based on Design of Experiment (DoE) technique for the optimization of an energy recovery ventilator (ERV). This system is one of the efficient ways to enhance the thermo-hygrometric comfort without increase excessively the thermal load in domestic kitchen. However, there is a major concern, which energy recovery cannot trade off ERV's fan power consumption. The goal of this study is to obtain the information about the relation between factors and response in an empirical way. This approach integrates three different levels of analysis: the virtual prototyping, Design of Experiment (DoE) and rapid prototyping. The virtual analysis allows to define the principal parameterization of a simplified model and to simulate the performance of each configuration at working condition. The proposed approach investigates the effect of the defined parameters and noise factor on the experimental results. In particular, the applied method for DoE analysis is based on virtual experiments in according to the necessity to reduce time and costs during the early design phase. The optimum parameters configuration, which is defined by the previous step, is useful to define the geometry and the working condition of a reliable virtual model. The final level is the realization of a 3D ERV with a rapid prototyping printer. The obtained component is now evaluable at the test bench to investigate the air flow rate and the electric power consumption.

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Keywords: Virtual Prototyping; Design of Experiments; Rapid Prototyping; Energy Recovery Ventilator.

1. Introduction

The goals of the European Community aim to develop a competitive sustainable and safety energy economy. In this sense, domestic appliance producers are faced with the study and research of more efficient products with less environmental impact [1], but that are able to get high performance and functionality [2]. These problems require a flexible design methodology that is able to support the engineer in virtual physical analyses and also in the rapid decision-making processes, in order to increase the quality and the performance of the product. Moreover, the complex dynamics of global markets, force companies to adopt new ways so as to increase their competitiveness. For this purpose have been developed a multidisciplinary approach, where the designer is obliged to consider simultaneously multiple perspectives to determine the optimal solution. Above all, engineer is called to achieve the right compromise among the product features, manufacturing time, cost and performance. This process of optimization is often manual [3] and does not allow a comprehensive exploration of the problem, obtaining solutions that are not always the optimal ones.

Therefore, automated optimization based on the integration of CAD and CAE tools are essential to increase products quality and to facilitate and accelerate the identification of the best configuration. The majority CAD-CAE tools existing on the market are stand-alone systems and they need a relevant user interaction to achieve a real integrated use [3,4].

In this context, the aims of this paper is to develop a methodology that allows, through the effective integration of different design and simulation tools, the multi-objective product optimization.

The approach presented in this paper consists in making a limited number of simulations based on the Design Of Experiments - DoE method [5–8] and the reconstruction of the Response Surface Methodology - RSM [9]. The simulation results are used to create an approximated model of system responses. The approximated model is called surrogate model or metamodel and can be generated using different techniques [10]. From the surrogate model it is possible to analyze thousands of configurations that identify, through the support of appropriate optimization algorithms, the optimal one. The proposed methodology has been applied to find the best configuration of a mechanical ventilation system. This sort of system is used in domestic environments to facilitate the air exchange. We are thus facing a multi-objective design, in which it is necessary to optimize the thermal comfort of the inhabitants and to minimize the energy consumption.

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2. Methodology

This section presents the methodology (shown in Fig.1) studied to support the *energy recovery ventilator - ERV* design for a domestic kitchen.
The achieved methodology integrates three different levels of analysis: virtual prototyping, design optimization and prototyping.
The proposed approach is based on virtual experiments according to the necessity of reducing time and costs during the first design phase. The optimum parameters configuration, defined by the previous step, is useful to define the geometry of a reliable virtual model. The final level is the realization of a 3D ERV with a rapid prototyping printer. The obtained component is now evaluable at the test bench to investigate the performance.
The virtual prototyping level concerns the phases of model simplification, geometrical parameterization and virtual simulation. The simplification of the virtual model is the first step where early analysis identifies the less important geometrical entities. At this level the engineer interacts with CAD tools to reduce the geometrical complexity of the real model. The resulting geometry is a closed volume which excludes through holes, threads, small fillets and chambers, electrical components, etc. The next step includes the parameterization of the main geometrical dimensions. Therefore, the parameters choice is related to the DoE analysis which requires an orthogonal array to plan the virtual experiments.
The design optimization guides the analysis of virtual simulation by identifying a certain number of parameters which influence the performance. The simulation basically regards CFD analysis which reproduces system behavior without physical manufacturing. Through the construction of the response surface it is possible to analyze the product in all operating conditions.
The DoE level provides the experiment plan definition related to the parameters chosen in virtual modeling. The engineer can use his know-how to set the parameters range and to evaluate the most suitable configuration. According to DoE approach, a reduced number of experiments is required to elaborate the final optimum condition. Each test includes a combination of the set values in order to investigate the influence of each parameter. The objective function includes three levels of specifications: the maximization of the ERV performance and the air flow temperature that entry in the kitchen and the minimization of the airstream velocity.
Analizyng the CFD results, it is possible to evaluate the optimum condition and to simulate the elaborated configuration.
The result of the design optimization approach, including the virtual experiments, provides a better parameters configuration. The elaborated settings could be simulated to evaluate the performance with virtual tools. The next step is the rapid prototyping of the better configuration, using a 3D printer tool. At the test bench, the real world experiments can confirm the final analyzed configuration of the printed model.
In the next sections this methodology will be applied in designing of an *energy recovery ventilator - EVR* for a single room ventilation.

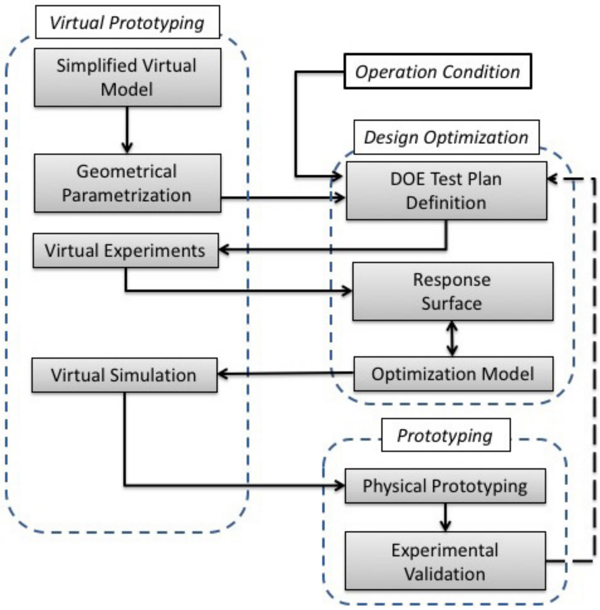

Figure 1: Scheme of the proposed methodology.

3. Numerical model

In this paper, the heat transfer and fluid flow characteristics of ERV are obtained by numerical simulation. The numerical simulation is performed using the commercial CFD code *ANSYS-Fluent*. The numerical model has been verified to be an accurate representation of real world through comparison with experimental test results. The CAD geometry of the model was generated in *SolidEdge*.

3.1. Geometry, mesh and boundary conditions

The geometry of ERV is modeled as a shell-and-tube heat exchanger. In heat transfer application the shell-and-tube heat exchanger is the most common type in use. This system offers several advantages such as: large heat transfer surface area-to-volume, easy manufacturing and disassembly, low cost etc...
In Fig.2 is shown the geometry of the ERV, it consists of a bundle of cylindrical tubes enclosed within a cylindrical shell. One fluid flows through the tubes and a second fluid flows within the space between the tubes and the shell.

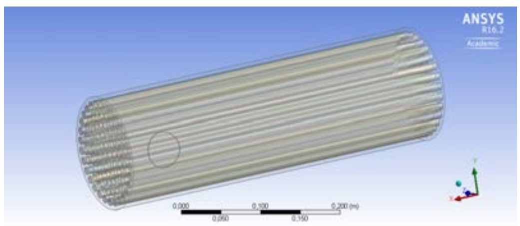

Figure 2: CAD geometry of the Energy Recovery Ventilator.

Table 1: Geometric and operating factors.

	Factors	Type	Value/Range	u.o.m
Geometric	Shell outer diameter D_s	Constant	150	[mm]
	Shell thickness s_s	Constant	2	[mm]
	Tube outer diameter D_t	Constant	10	[mm]
	Tube thickness s_t	Constant	0,5	[mm]
	HVR length L_{ERV}	Constant	450	[mm]
	Number of tubes n_t	Constant	95	
Operating	Inlet temperature supply air mass flow $T_{i,s}$	Constant	$278,15$	[K]
	Inlet temperature exhaust air mass flow $T_{i,e}$	Constant	$298,15$	[K]
	Supply air mass flow $\dot{m}_s$	Variable	$0,015 \div 0,08$	$[\mathrm{kg\,s^{-1}}]$
	Exhaust air mass flow $\dot{m}_e$	Variable	$0,015 \div 0,08$	$[\mathrm{kg\,s^{-1}}]$

The ERV considered in this study is designed to fit into a standard domestic kitchen ventilation hole. Therefore, for a mean Italian home, it has to have 150 [mm] of radius and 450 [mm] of length. The inner tubes thickness is 2 [mm].
Mesh generation is performed using a structured, non-uniform mesh system of polyhedra elements within the mesh generator of *Ansys*.
The supply and exhaust airstreams heat exchange in a counter-current flow arrangements. Both the flows are assumed to be incompressible, single-phase, steady-state, turbulent and uniform at the inlet and outlet of the ERV. Aluminum was chosen as material for the tubes. Physical properties are supposed to be constant with temperature and velocity. Adiabatic boundary condition is adopted in the outer wall of the shell. For the inlet boundary mass flow rate was chosen while for the outlet boundary pressure outlet boundary condition was chosen.
In Tab.1 are shown the value of the main geometric and operating parameters.

3.2. Governing equation

The numerical simulation was carried out assuming a 3D steady-state turbulent flow. Considering this assumption, the governing equations of mass, momentum and energy conservation were modified as follows:

Continuity equation:

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{1}$$

Momentum equation:

$$\frac{\partial}{\partial x_i}(\rho u_i u_k) = \frac{\partial}{\partial x_i}\left(\mu \frac{\partial u_k}{\partial x_i}\right) - \frac{\partial p}{\partial x_k} \tag{2}$$

Energy equation:

$$\frac{\partial}{\partial x_i}(\rho u_i T) = \frac{\partial}{\partial x_i}\left(\frac{k}{C_p}\frac{\partial T}{\partial x_i}\right) - \frac{\partial p}{\partial x_k} \tag{3}$$

where u is the velocity; x the direction; ρ the density; μ dynamic viscosity; p the pressure; T the temperature; C_p the heat capacity at constant pressure and k the fluid thermal conductivity.

In this article, the shear-stress transport (SST) k-ω viscous model is adopted. Transport equations for SST k-ω model are:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_k}\left(\Gamma_k \frac{\partial k}{\partial x_k}\right) + \tilde{G}_k - Y_k + S_k \tag{4}$$

$$\frac{\partial}{\partial t}(\rho \omega) + \frac{\partial}{\partial x_i}(\rho \omega u_i) = \frac{\partial}{\partial x_k}\left(\Gamma_\omega \frac{\partial \omega}{\partial x_k}\right) + G_\omega - Y_\omega + D_\omega + S_\omega \tag{5}$$

where $\tilde{G}_k$ represents the generation of turbulence kinetic energy due to mean velocity gradients; G_ω the generation of ω; Γ_k and Γ_ω the effective diffusivity of k and ω; Y_k and Y_ω the dissipation of k and ω due to turbulence; D_ω the cross-diffusion term and S_k and S_ω are user-defined source terms.

3.3. Solution method

The governing equations are solved by the *COUPLED* algorithm. The *COUPLED* solution method solves the governing equations simultaneously giving a more robust and efficient single phase implementation for steady-state flows. Second-order upwind scheme was chosen for the discretization of the convection terms of each governing equation and pseudo-transient approach was enabled for the numerical simulation. The convergence criteria was set to the tolerance of 10^{-4}.

4. Optimization analysis

4.1. Response surface methodology (RSM)

Response Surface Methodology (RSM) consists of a group of statistical and mathematical techniques useful in the development, improvement and optimization of systems/processes/services. This method is widely used in industry, especially in situations where there are many input variables that potentially affect the measurements of system characteristics[11]. The goal is to simultaneously optimize the levels of these variables in order to obtain the best performance. Input variables (or independent variables), the values of which can be controlled and set by the experimenter, are called factors. The response variable (or dependent variable) is the measured quantity, the value of which is affected by the levels fac-

tors changes.
The application of RSM takes concrete form by determining the approximate functional relationship between the input variables and the response of the system to be optimized. Typically second order polynomials expressions are used.
The relationship between the response and the inputs is given by:

$$y = f(x_1, x_2, \ldots, x_n) + \epsilon \tag{6}$$

where y is the response, f is the unknown function of response, x_1,x_2,...,x_n denote the independent variables, n is the number of the independent variables and finally ϵ is the statistical error. It is generally assumed that ϵ has a normal distribution with mean zero and variance.
RSM consists of the following steps:

1. choice of the major effect factors on the system and delimitation of the experimental domain;
2. designing a set of experiments in order to have adequate and reliable measures of the interest response;
3. determining the mathematical model that best interpolates data obtained from designed experiments;
4. identification of the input variables optimum values that produce the maximum(or minimum) value of the response.

4.2. Design of Experiments (DoE)

An experiment is a test or a series of tests in which purposeful changes are made to the input variables (factors) of a process so that we may observe and identify the reasons for changes in the output response/s.
In industrial design the realization of tests is always a major source of costs, both as employment of time and of human,material and computational resources.
The *Design of Experiments - DoE*[5] is a statistical methodology to approach the design and organization of experiments that allows to get as much information as possible with the minimum amount of resources, i.e. with the smaller possible number of experiments.
Usually the most immediate experimental procedure consists in performing one or more tests, for each value of the investigated independent variable, leaving unchanged all the other conditions:*One Factor At a Time-OFAT* approach. The effects evaluation of the other parameters variation is obtained by repeating the same type of procedure for each of them. OFAT method doesn't study contemporary the variations effects of two or more parameters. On the other hand, the DoE methodology is based on tests characterized by the simultaneous variation of more parameters [12].
The first step of the DoE is the choice of the factors, the number of the levels, the range of the variability intervals and the response variable. Then the proper experimental design is defined and the experiment is conducted. Finally, the obtained data are statistically processed to generate the response surface.
There is a large amount of experimental designs in the literature. Central composite design (CCD) method is applied in this simulation. It has been described by Box and Wilson in 1951 and it is one of the most used second-order models[13] because it is extremely simple to use and it allows estimation of all parameters in a full second-order model. It consists (Fig.3) of a two-level full or fractional design (corner points), an additional

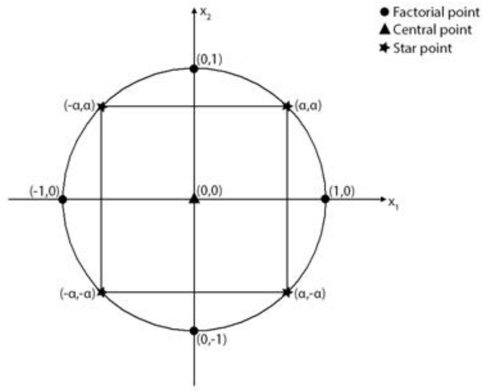

Figure 3: Example of central composite design for 2 factors with $\alpha < 1$. Symbol points are the experiments of the design.

design (star points), that allow curvature estimation, and a point at the center of the design space (center points). If the distance of a factorial point from the center of the design space is ± 1 unit for each factor, the distance of a star point from the center of the design space is $\pm\alpha$. The value of α depends on the design and on the number of factors involved[14].

4.3. The choice of factors

The response of a system may be affected by several factors and it is practically impossible to identify and study each minimum contribution. Moreover, more are the effects to consider and less accurate, necessarily, will be the experimental fitting of the obtained data. Therefore, to contain the costs(computational and of resources) and to make the analysis more precise, it is necessary to choose those factors with major impacts on the response. In case of complex design, where it is not easy to know the cause-effect relationship between factors and response, a screening design should be carried out to individuate which variables have more significant effects.
In this case, in addition to the geometric parameters described above, it is possible to identify the operating parameters. The variables concern the incoming and outgoing flows of the room and the inside and outside temperatures.
In this paper to optimize an energy recovery ventilator, two factors are considered: exhaust air mass flow and supply air mass flow. The range of variation of these variables is shown in Tab.1. The values of the temperature are fixed as required the energy consumption testing of these devices [15].

4.4. The choice of responses and the goals of optimization

For a single room, it is important to have an efficient ventilation and as large as possible heat recovery. Moreover, the emission of noise from the units should be low. To evaluate that, the following characteristics of the ERV are analyzed: thermal efficiency η_t, temperature and velocity of the airstreams on inlet and outlet sections.
The thermal efficiency of the ERV η_t is index of recovered heat

Table 2: DoE matrix and simulation results.

No.	Factors		Response				
	$\dot{m}_s$ [kg s^{-1}]	$\dot{m}_e$ [kg s^{-1}]	$T_{o,s}$ [K]	$T_{o,e}$ [K]	v_s [m s^{-1}]	v_e [m s^{-1}]	η_t
1	0,02375	0,0475	288,02	288,73	4,18	9,86	0,49
2	0,02375	0,015	283,81	281,35	4,18	3,12	0,90
3	0,02375	0,08	289,54	291,67	4,18	16,60	0,57
4	0,0075	0,0475	294,17	293,28	1,32	9,86	0,80
5	0,04	0,0475	285,11	286,95	7,04	9,86	0,59
6	0,0075	0,015	290,83	286,18	1,32	3,12	0,63
7	0,0075	0,08	294,89	295,11	1,32	16,60	0,84
8	0,04	0,015	281,70	280,33	7,04	3,12	0,95
9	0,04	0,08	286,60	290,04	7,04	16,60	0,42

and saved energy and is defined as:

$$\eta_t = \frac{C_{p,s}\dot{m}_s(T_{o,s} - T_{i,s})}{min(C_{p,s}\dot{m}_s, C_{p,e}\dot{m}_e)(T_{i,e} - T_{o,e})} \tag{7}$$

The supply airstream outlet temperature $T_{o,s}$ is significative in order to assess the perceived environmental comfort. In fact, cold drafts create discomfort situations.
The evaluation of the airflows velocities are related to the noise generation and to the environmental comfort: the more the velocity is high the higher will be the noise and the less the comfort.
The ideal situation, from a environmental comfort point of view, is that the refresh airstream outing from the EVR has the temperature as high as possible and the velocity as small as possible.
Definitily, the optimization analysis of the EVR is carried out setting as goals the maximization of the thermal efficiency η_t and supply airstream outlet temperature and the minimization of the airflows velocities.
In this paper to solve this multi-objective optimization the *Multi-objective Genetic Algorithm - MOGA* [16] is used. It is recognized as one of evolutionary algorithms with higher performance and, therefore, is one of the most used in the problems of multi-objective optimization. This algorithm, based on the Darwin's evolutionary theory, starting from a population of individuals that evolves from generation to generation, it performs a heuristic search that favors the areas of the search space where it is most probable to find optimal solutions.

5. Results and discussion

The aim of this study was to develop a methodology that enables engineers to find optimal solutions quickly and easily. In particular, in this paper an ERV for a single room ventilation is optimized.
In Tab.2 the DoE matrix whit the results of computational fluid dynamic simulations are reported. These results, through RSM, are regressed so as to obtain the plots shown in Fig.4,5.
In order to save energy and to avoid thermal discomfort, good heat recovery is needed. It is evident from the results (Fig.4)

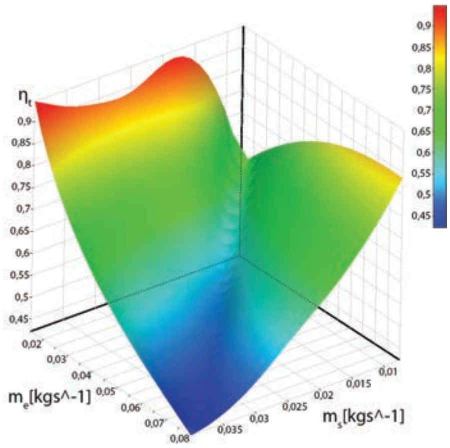

Figure 4: Thermal efficiency η_t as function of the air mass flows.

that a great heat recovery (evaluated by η_t) can be achieved using this device, especially when $\dot{m}_e$ and $\dot{m}_s$ are respectively at opposite ends of the variation range.

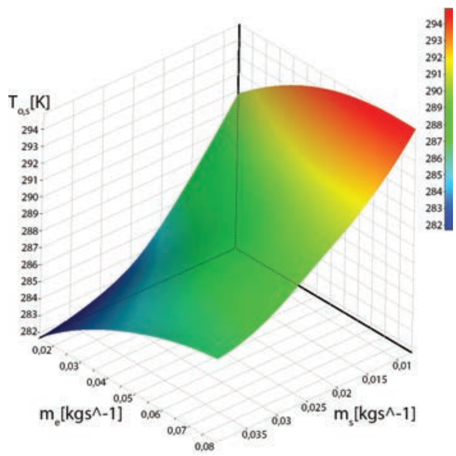

Figure 5: Temperature of the supply airflow outing from the heat recovery ventilator $T_{o,s}$ as function of the air mass flows.

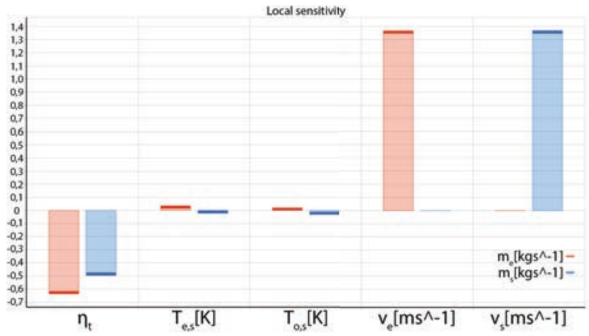

Figure 6: Sensitivity histogram between responses and factors.

In order to avoid discomfort situations is significative to have high $T_{o,s}$ and low airstreams velocities.
Fig.5 shows the response of $T_{o,s}$ to the air mass flows variation. Comparing Fig.4 with Fig.5 it is possible to observe that to have high value of η_t not necessary means to have high value of $T_{o,s}$. No fluids velocity plot is reported because by the continuity equation is known the directly proportional to mass flow.

The Fig.6 shows the sensitivity histogram. Through this analysis is possible to evaluate the variables calculated dependencies as function of the chosen input parameters. It is interesting to note how η_t is more sensitive to $\dot{m}_e$ than $\dot{m}_s$.
It is evident how to individuate *by-eye* which are the optimal mass flow value is unfeasible, considering also that some goals are conflicting. Therefore, to orient, support and monitor, the MOGA algorithm has been used. In Tab.3 are shown three optimal space points design, i.e. those that allow to maximize heat recovery and $T_{o,s}$ and to minimize airstreams velocity, individuated by the MOGA algorithm.

Table 3: Optimal space points design.

$\dot{m}_e$ [kg s^{-1}]	$\dot{m}_s$ [kg s^{-1}]	η_t	$T_{o,s}$ [K]	v_{max} [m s^{-1}]
0,0769	0,0076	0,82	294,84	13,56
0,0701	0,0076	0,83	294,81	12,36
0,0575	0,0075	0,82	294,61	10,19

6. Conclusion

The proposed approach has been validated during the design of a energy recovery ventilator for domestic buildings.The main geometrical and operating parameters have been analyzed and it has been defined a Central Composite Design in order to plan the necessary virtual experiments. Using a CFD tool has been simulated the fluid dynamic performance for each planned experiments. The geometrical model, has been previously simplified using a parametrical approach. An objective function has been formulated so as to give a value to each virtual experiment. The evaluation criteria are based on maximizing the efficiency of the system and minimizing the exchanged air flow. After the simulation calculation, an optimal configuration has been found. The new configuration is then validated by CFD analysis. The use of the Response Surface method allows a decreases in the number of experiments, while the introduction of virtual prototyping reduces pilot manufacturing. The construction of the response surface allows to know the product performance without carrying out the test on every working point.
Definitely, DoE techniques has been proven to be a practical and an effective design tool that can help engineers in systems design under different operating conditions.
As a future development, the proposed methodology will be extended to the design of a new energy recovery ventilator. In particular a different type of heat exchange will be analyzed in order to validate the design approach.

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